Naval Submarine Medical Research Laboratory

Memorandum Report No. 05-06 14 February 2005

VIRGINIA TRUNK LIMITATIONS DCS RISK CALCULATIONS

P. K. WEATHERSBY, Ph.D.

Approved and released by:
J. C. Daniel, CAPT, MC, USN
Commanding Officer
Naval Submarine Medical Research Laboratory

VIRGINIA TRUNK LIMITATIONS DCS RISK CALCULATIONS

P. K. WEATHERSBY, Ph.D.

Naval Submarine Medical Research Laboratory
Memorandum Report 05-06

Approved and Released by:

J. C. Daniel, CAPT, MC, USN
Commanding Officer
NAVSUBMEDRSCHLAB

ADMINISTRATIVE INFORMATION

The views expressed in this report are those of the authors and do not reflect the official policy or position of the Department of the Navy, Department of Defense, or the U.S. Government. This report was approved for publication on 14 February 2005 and has been designated as NavSubMedRschLab Report #05-06.

Summary

The incremental increase from prior decompression sickness (DCS) risk estimates due to waiting an additional 5 seconds for the escape hatch to fully open is estimated at only 0.1 to 0.3% DCS risk. This estimate applies to 600-foot escapes both from an unpressurized ship with a variety of pressurization profiles, and for the 11 foot (about 1 1/3-atmosphere) saturation case. The increase is clearly minor and well within the uncertainty of the base predictions provided previously.

Estimation of six hundred foot escape after saturation from 23 feet is harder to answer. The main mathematical model (USN93) predicts a DCS rate of 13.5%, and after adding 2 standard deviations for model uncertainty and a 30% bias correction, this yields an upper bound of 21%. For the same escape from 11 feet pressurization, the same upper bound gives an escape DCS probability of 9 %. However, USN93 is known to be less accurate with saturation exposures in that range. A recent UK model with the same limitations provides similar results. After examining the raw data of human saturation exposures, and a recent model of them by Lillo and colleagues, it appears that 600 foot escape from 23 feet saturation carries about an 8% risk of DCS.

The risk estimates refer to the full range of DCS symptoms. An unpublished description of expected severity by Thalmann and Weathersby suggested that a DCS risk at less than 10% would result in a “probability of very few permanent problems” and that DCS risk of 10-20% would “ include some cases requiring recompression within a few hours”.

Better estimates could be made from a purpose-built submarine escape DCS model, which we have proposed to develop. Much better estimates should be available in one year, at the successful completion of the project “DISSUB escape from depths greater than 600 fsw".

Background

The problem in slow opening of the VIRGINIA hatch was discussed in reference (1). For purposes of DCS risk estimation, the effect of concern is to delay the escaper's departure from the trunk after reaching full seawater pressure, by an additional time increment of 3 to 5 seconds.

The other question, which arose in reference (1), is the effect of a 23-foot prior saturation. This depth has been a line of demarcation in published U.S. Navy Guard Books since 2000. The earliest US guidance (ref 2) mentioned 18 feet as an internal pressurization with no concern for DCS after rescue, but did not provide quantitative guidance on escape from a pressurized submarine. However, Appendix B in that document did include a UK curve, indicating a "Safe to Escape" boundary at about 23 feet internal pressurization with an escape depth of approximately 300 feet. The same curve's shallow boundary terminated at 26.4 feet pressurization and zero depth escape, and deep boundary terminated at about 750 feet with a boat at one atmosphere. The curve can be tracked to a presentation by CDR R. Whiteside, RN at a 1987 meeting (ref 3). No precision was indicated, and the source was said to be a limited number of animal experiments. The 2003 UK Guard Books apparently recommend no escape from any depth when internal pressure exceeds 23 feet, and restricts escape depth to 300 feet as the interior pressure approaches 23 feet. (The UK's full 600 feet escape depth is only recommended for internal pressurizations below 16.5 feet.)

Risk from Hatch Opening Delay

Several programs are now available to estimate DCS risk. The one most applied (and the one used in a 2000 NAVSEA contract report - ref 4); and in a journal report plotting escape risks for the Mk-VIII SEIE - ref 5) is called USN93. The mathematical structure has been published in both a government report (ref 6) and a journal article (ref 7). The final parameters of the USN93 model are found in (ref 8).

A variety of cases estimating risk of DCS are presented in Table 1. Some are identical to those used in (ref 4). For the new question at hand, the at-sea TOLEDO pressurization profile was used mostly, and the escaper's time at 606 feet was increased by another 5 sec to simulate the slower opening VIRGINIA hatch.

Table 1. Estimated Risk of DCS from Pressurization + Escape

Case	Depth (feet)	Initial comp Press	Ratio in 4 sec	Time at max Depth (sec)	Comments / Delay	% DCS Risk	
						Point	Max
1 *	600	1.0 atm	1.8	10	Initial 688 design goal	2.2	6
2	600	1.0 atm	~1.7	10	VA LET 2-men calcs dtd 9/29/04 Flood line K	2.2	6
3	600	1.0 atm	~1.5	10	VA LET 1-man calcs dtd 9/29/04 Flood line K	2.2	6
4 *	606	30 ft over 1 min+	<1.7 as meas.	10	Run1 on SSN 769, Dec 99	2.3	6
5	606	30 ft over 1 min	<1.7 as meas.	15	Run1 on SSN 769, Dec 99 + 5 sec at 606 for slow opening	2.5	7
6 *	606	30 ft over 1 min	<1.7 as meas.	25	Run1 on SSN 769, Dec 99, plus 15 sec at 606 for even slower opening	2.9	7
7 *	606	11 ft sat; 30 ft over 1 min	<1.7 as meas.	10	Run1 on SSN 769, Dec 99, with compartment previous at 1 1/3 atm	4.1	9
8	606	11 ft sat; 30 ft over 1 min	<1.7 as meas.	15	Run1 on SSN 769, Dec 99, with compartment previous at 1 1/3 atm + 5 sec at 606 for slow opening	4.4	9
9	606	11 ft sat; 30 ft over 1 min	<1.7 as meas.	25	Run1 on SSN 769, Dec 99, with compartment previous at 1 1/3 atm + 15 sec at 606 for even slower opening	4.9	10

Notes for Table 1: Columns contain: the case number for easy reference, the escape trunk depth, the internal pressure of the submarine escape compartment, the initial rate of pressure doubling in the trunk during flooding, the time which escapers are at maximum depth before starting ascent, comments and both the point and upper bound estimates of DCS risks. The upper bound consists of the upper 95% confidence limit on the USN93 model point prediction, plus another 30% to allow for a possible bias in model calibration, as discussed in references (4) and (5). Cases marked with an asterisk (*) are identical to those used in reference (4).

For an unpressurized compartment, at the design goal pressurization rate of doubling in 1.8 sec, (case 1), DCS risk is slightly above 2% (upper bound about 6%). The same result is also obtained in both the slightly slower calculated pressurization rates in

VIRGINIA for 2-men and 1-man in the trunk (cases 2 and 3). In the 2-mannequin at-sea data from TOLEDO (case 4), the pressure initially rose 30 feet during a 1-minute vent, but the DCS rate is scarcely affected. Delays of 5 sec (case 5) or even 15 sec (case 6) only increase the estimated DCS rate by a very slight amount.

The next several cases acknowledge that a modest increase in internal submarine pressure might well have occurred by the time escape begins. Eleven feet, or 1 1/3 of an atmosphere, was simulated to have occurred several days earlier (long enough for a saturation exposure). Case 7 adds this saturation to case 4. The increased risk is noticeable, going over 4%. The additional delay at 600 feet by 5 sec (case 8) or 15 sec (case 9) has only a marginal additional impact on risk. All these exposures are expected to incur less than 10% DCS, even when a conservative upper bound is produced.

From discussions below, it now appears that the effect on DCS rates of 11 foot saturation will be even less than the estimates in the prior paragraph (most likely an increment of <1% risk over an unpressurized compartment).

Risk from escape after internal pressurization of 23 feet

Predictions made from a pressurized submarine have an important component of risk from air saturation followed by rapid decompression. (Work in that decompression regime has been supported in recent years under submarine rescue, as transfer under pressure cannot be assured). Even when first published, the USN93 algorithm was known to incorrectly predict human data from rapid decompression after 20 feet of air saturation. Since the publication of USN93, an additional 40% of air saturation data have been compiled. The full amount of human data (245 exposures) available from (ref 9) is presented in Table 2.

Table 2 Risk of DCS from pressurization and surfacing only

Sat pressure, feet	20	21	22	23	24	25	26	30	33
DCS / exposures	0/62	0/35	2/23	0/6	1/18	4/25	2/39	4/16	8/21
Data incidence, %	0	0	9	0	6	16	5	25	38
USN93 prediction, %	7	8	9	10	11	12	13	16	19
Sat. Hill model, %	2	3	4	5	6	8	10	22	34

Notes for Table 2: The numerical entries across the first row are air saturation depths of human experimental exposures with precise pressure control for days. The second row is the number of DCS cases observed and the total number of subjects exposed to each depth. The following row is the raw percentage incidence of DCS from the data. Point predictions from Model USN93, and another model to be discussed are the final 2 rows.

The row labeled "DCS / exposures" shows that most depths have relatively few experiments to reliably estimate an incidence. Taking the data at 23 feet, an outcome of zero DCS in 6 exposures has a 95% binomial upper confidence limit on the data of 46% incidence. Despite the limited binomial precision afforded by the small number of exposures, a clear trend is seen in the data of a low incidence until about 25 feet, and then a rise up to 25% DCS or more above 30 feet pressurization. The USN93 model, on the other hand, seems to systematically overestimate the data below about 24 feet, and underestimate the data at depths of 30 feet and deeper. Statistically significant statements about the USN93 "misses" can only be made at the extreme ends of the data.

At 23 feet saturation, the USN93 prediction is 10% DCS, with 95% model confidence limits of 8 to 12%. The combined data of 22, 23, and 24 feet is 3 DCS events in 47 exposures for an estimated incidence of 6%, and binomial confidence limits of 1 to 18%. So, even combining adjacent depths, there is not sufficient raw data to clearly contradict the USN93 prediction at that point. Nevertheless, a better model of the data in the first three rows of Table 2 would definitely be desirable.

Saturation exposures followed by direct surfacing have recently been modeled directly by Lillo and colleagues, using a 2-parameter Hill function over only these types of exposures (ref 10). In addition to the 245 human points in Table 2, another 128 pig experiments and 525 rat experiments were included in their analysis. Three 50% incidence location parameters, separate for each species, and a common steepness-at-50% parameter, applied to all three species, were estimated. The animal data were shown to strengthen the precision of the human estimates compared to using only human data, and the "combined species" parameters are used here. These "Sat. Hill model" entries in Table 2 follow the experimental human data trend more closely than USN93, staying low below 25 feet, then rising rather steeply. The Sat. Hill estimate at 23 feet of 5 % risk (95% model confidence limits of 1 to 8% DCS risk) is taken as the <u>best</u> estimate of human DCS for direct surfacing from that exposure.

The USN93 algorithm with a compartment saturation depth of 23 feet, followed by a 600 foot escape following a SSN 769 pressurization predicts 13.5% DCS with an upper bound of 21%. From Table 2, we expect this estimate to be high by about 5% (the difference between the Hill sat model and USN93 for the case of 23 feet saturation without escape). Therefore the more plausible prediction is about 8% DCS. A plausible upper bound is perhaps 15%.

A more recent UK report goes further in applying animal experiments to submarine escape and rescue (ref 11). That report combines most of the data in the USN93 predictions with some yet unpublished UK human and goat escape trials (with a goat treated mathematically as responding identically as a man), in several reformulated models. Their recommended model grafts the Hill sat model of Lillo as an upper boundary onto a re-parameterized USN93 framework. That model estimates about 13% DCS for a 600-foot escape from a submarine pressurized to 23 feet. Precision of the model estimates are only partially provided by the paper, but appear to be 5% or more. Of note, the recommended model cannot be used to explore different submarine pressurization histories, such as the increase due to the escape cycles themselves.

A final example demonstrates the versatility of a general model such as USN93 (with its limitations in mind). In this case, a long saturation at 11 feet in the submarine is assumed. Then the escape evolution itself for a large number of survivors is assumed to add air into the boat, increasing internal pressure by another 12 feet (to an eventual total of 23 feet) over a period estimated at 12 hours. USN93 is used to estimate the DCS risk for the final escaper at 600 feet after the pressurization just described. (Model USN93 has been shown to estimate DCS well in multi-hour Special Warfare shallow dive profiles - see ref 12). The estimated DCS risk of 8% (with an upper bound of 14%) seems more appropriate than the 13% or so that are estimated for full saturation at 23 feet by either USN93 or the recent UK model. And, the over prediction of USN93 at 11 foot saturation makes the most plausible answer somewhere closer to 6%.

Some comment about DCS severity is possible, based on data review and professional judgment. The following categorical descriptions were developed to accompany use of the USN93 model in submarine escape planning (E.D. Thalmann and P.K. Weathersby, unpublished, 1996):

Under 10% DCS risk	**Probability of very few permanent problems.**
10% < DCS risk < 20%	**Includes some cases requiring recompression within a few hours.**
20% < DCS risk < 50%	**Range of probabilities that may lead to death in some and permanent disability without immediate therapy in most.**
Over 50% DCS risk	**Expected to be frequently fatal; no experimental data in this range.**

Prospects

Model USN93 and the UK variants are calibrated on less than the full amount of human deep submarine escape data. Both included 40 human escape trials from depths between 400 and 600 feet in their calibration data sets of about 3000 total exposures. However, another 150 human trials (ref 13) in the depth range of 300 to 505 feet have yet to be used in model calibration. Moreover, USN93 was deliberately developed for the operational range of Navy divers, and included hundreds of profiles (repetitive dives, Mk 16 dives with constant 0.7 ATA oxygen, etc.), which heavily influence the estimated parameters, but do not directly bear on submarine escape or saturation exposures. A probabilistic mathematical model purpose-built for DISSUB applications has never been developed. In lieu of that more appropriate model, we use wide confidence limits and bias offsets in USN93 predictions, and then apply post-hoc corrections based on known model deficiencies.

The purpose-built model is planned to be available in FY05. <u>Substantial improvements in our ability to make DCS risk predictions at all escape depths are expected</u> from the FY05 NSMRL-EB-NEDU project “DISSUB escape from depths greater than 600 fsw". That assumes, of course, that the project is funded.

References

(1) Meeting at NSMRL (CDR Horn, Dr. Weathersby) with EB (Mr. Whitney) 11 Oct 2004.

(2) Pressurized submarine rescue. A manual for undersea medical officers. C.A. Harvey, D.M. Stetson, A.C. Burns, P.K. Weathersby, J.W. Parker, and D.M. Mole. Groton, CT: Naval Submarine Medical Research Laboratory Report 1178, 62 pp. June 1992.

(3) DSRV-MOSUB Pressurized operations - the UK scenario. R.C. Whitesides. in: Proceedings of the Sixth Tripartite Conference on Submarine Medicine. P.K. Weathersby and J.C. McNary, editors. Groton, CT: Naval Submarine Medical Research Laboratory Special Report SP90-3, p 25-31. Oct 1990.

(4) Summary of Submarine Escape Risk Estimates Based on A review of "Medical Considerations that Drive the Development of a Pressurization Profile and Medical Escape Timeline for Deep Escape." Report of the Electric Boat Corporation Enclosure to EB letter 492:MW-99-903048/5.12 dated 20 July 1999 by P.K. Weathersby, PhD, CAPT, MSC, USN (ret). Performed for Naval Sea System Command Code PMS 395 Under Portsmouth Naval Shipyard Contract N00102-99-M-1306. Initial Issue: 21 February 2000, Final Issue: 07 April 2000.
[+] Note: In that document, Table 1 lists 33 feet as the post-ventilation trunk depth in the TOLEDO tests. Re-inspection of the data shows that 30 feet is a better number. The risk predictions from 30 or 33 feet do not differ within the reported precision shown in Table 1 above.

(5) Escape from a Disabled Submarine: Decompression Sickness Risk Estimation. E.C. Parker, R. Ball, P.M. Tibbles, and P.K. Weathersby. Aviation Space and Environmental Medicine, Vol. 71, pp. 109-114, 2000.

(6) Statistically based decompression tables. VIII. Linear-exponential kinetics. E.C. Parker, S.S. Survanshi, P.K. Weathersby, and E.D. Thalmann. Technical Report of the Naval Medical Research Institute, Bethesda, MD: NMRI 92-73, 60 pp. Sept 1992.

(7) Improved probabilistic decompression model risk predictions using linear-exponential kinetics. E.D. Thalmann, E.C. Parker, S.S. Survanshi, and P.K. Weathersby. Undersea and Hyperbaric Medicine, Vol. 24:255-274, 1997.

(8) Statistically based decompression tables XII. (Volume I) Repetitive Decompression Tables for Air and Constant 0.7 ATA PO_2 in N_2 using a Probabilistic Model. 99 pp. (Volume II) Repetitive Dive Tables: Air. 173 pp. (Volume III) Exceptional Exposure Tables: Air. 193 pp. (Volume IV) Repetitive Dive Tables: 0.7 ATA PO_2 in N_2. 157 pp. (Volume V) Exceptional Exposure Tables: 0.7 ATA PO_2 in N_2. 105 pp. S.S. Survanshi, E.C. Parker, E.D. Thalmann, and P.K. Weathersby.

Technical Report of the Naval Medical Research Institute, Bethesda, MD: NMRI 97-36, August 1997.

(9) The dive profiles and manifestations of decompression sickness cases after air and nitrogen-oxygen dives. Vol. I: Data set summaries, manifestation descriptions and key files, Vol II: Complete profiles and graphic representations for DCS events. D.J. Temple, R. Ball, P.K. Weathersby, E.C. Parker, S.S. Survanshi. Silver Spring MD: Naval Medical Research Center Technical Report 99-02, 1999.

(10) Using animal data to improve prediction of human decompression risk following air-saturation dives. R.S. Lillo, Himm, J.F., Weathersby, P.K., Temple, D.J., Gault, K.A., and Dromsky, D.M. 2002. Journal of Applied. Physiology. Vol 93: 216-22, 2002.

(11) Safe to escape curve for man. G.A.M. Loverman, Jurd KM, Sneddon FM, Thacker JC, Stansfield MR. Farnborough UK: QinetiQ Ltd. Report QINETIQ/KI/CHS/CR032393/1.0. Oct 2003.

(12) Statistically based decompression tables. XI: Manned validation trial of the LE probabilistic model for air and nitrogen-oxygen diving. E.D. Thalmann, P.C. Kelleher, S.S. Survanshi, E.C. Parker, P.K. Weathersby. Silver Spring MD: NMRC Joint Technical Report 99-01 and NEDU 1-99, 81 pp. 1999

(13) Submarine escape breathing air. A review and analysis of animal and human experiments by the Royal Navy. K.W. Donald. Bulletin of European Physiopathology and Respiration. Vol 15: 739-754, 1979.

Acknowledgement

I thank Rich Lillo and Keith Gault of the Navy Experimental Diving Unit for additional material related to the Sat. Hill model of (ref 10).

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
14-02-2005	Memorandum Report	Oct 2004 - Dec 2004

4. TITLE AND SUBTITLE	
VIRGINIA TRUNK LIMITATIONS DCS RISK CALCULATIONS	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
P.K. WEATHERSBY, PH.D.	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
NAVSUBMEDRSCHLAB Box 900 Groton, CT 06349-5900	MEMORANDUM REPORT #05-06

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, Distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The incremental increase from prior decompression sickness (DCS) risk estimates due to waiting an additional 5 seconds for the escape hatch to fully open is estimated at only 0.1 to 0.3% DCS risk. This estimate applies to 600-foot escapes both from an unpressurized ship with a variety of pressurization profiles, and for the 11 foot (about 1 1/3-atmosphere) saturation case. The increase is clearly minor and well within the uncertainty of the base predictions provided previously.

Estimation of six hundred foot escape after saturation from 23 feet is harder to answer. The main mathematical model (USN93) predicts a DCS rate of 13.5%, and after adding 2 standard deviations for model uncertainty and a 30% bias correction, this yields an upper bound of 21%. For the same escape from 11 feet pressurization, the same upper bound gives an escape DCS probability of 9%

15. SUBJECT TERMS

decompression sickness, submarine escape

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					M. Fitzgerald, Publications Manager
U	U	U		11	19b. TELEPHONE NUMBER *(Include area code)* (860) 694-2442

However, USN93 is known to be less accurate with saturation exposures in that range. A recent UK model with the same limitations provides similar results. After examining the raw data of human saturation exposures, and a recent model of them by Lillo and colleagues, it appears that 600 foot escape from 23 feet saturation carries about an 8% risk of DCS.

The risk estimates refer to the full range of DCS symptoms. An unpublished description of expected severity by Thalmann and Weathersby suggested that a DCS risk at less than 10% would result in a "probability of very few permanent problems" and that DCS risk of 10-20% would " include some cases requiring recompression within a few hours".

Better estimates could be made from a purpose-built submarine escape DCS model, which we have proposed to develop. Much better estimates should be available in one year, at the successful completion of the project "DISSUB escape from depths greater than 600 fsw".